Spaceborne Polarimetric SAR Interferometry: Performance Analysis and Mission Concepts

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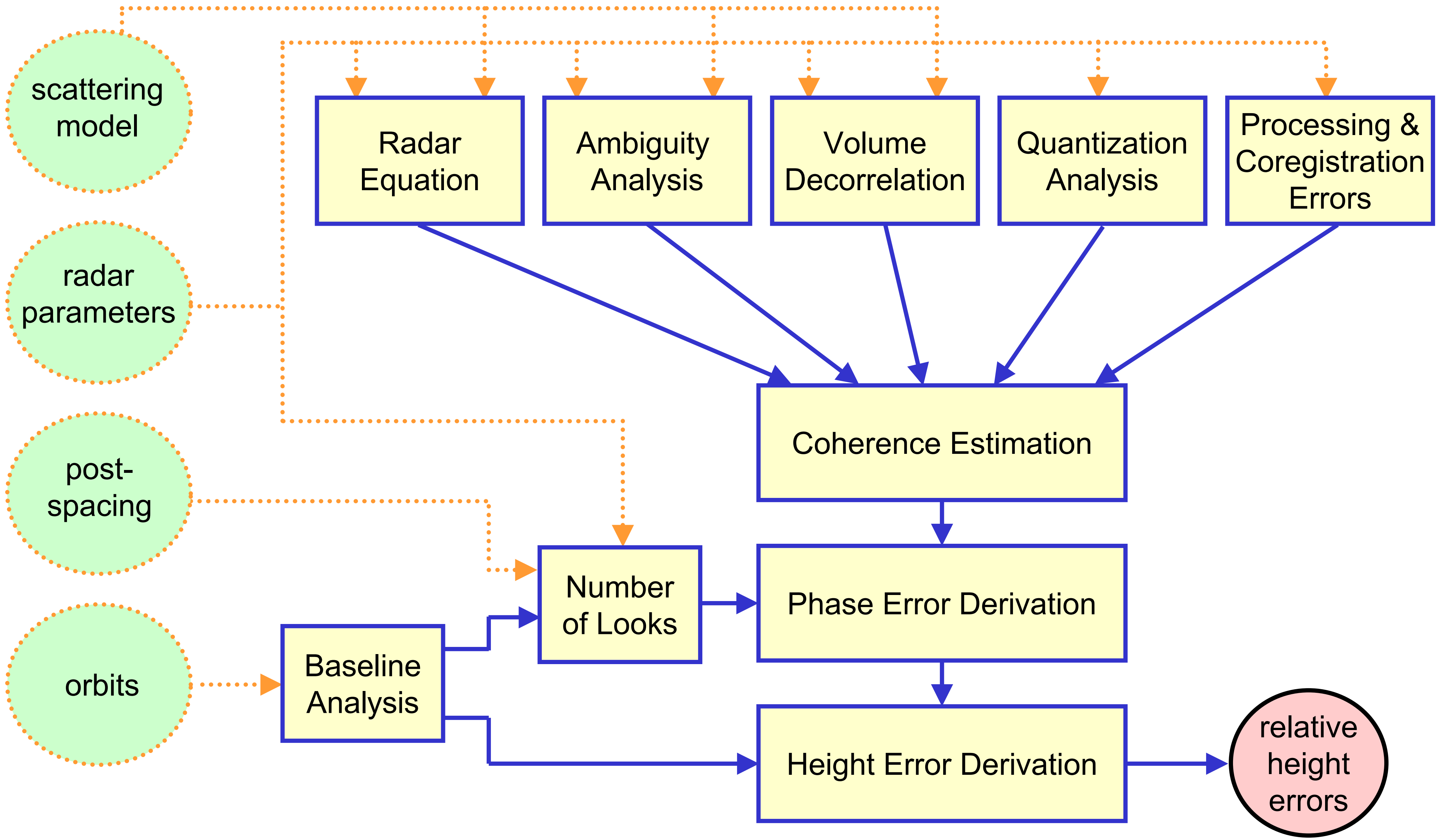
Overview

- *Outline of Performance Analysis*
- *Repeat Pass Mission Scenarios*
- *Single Pass Mission Scenarios*
- *Critical Issues*

Performance Analysis



L-Band Mission Scenario: Forest

Data for Scots Pine Forest (from S. Cloude et al., 2004)

Parameter	Value
Height	18 m
Incident Angle	45°
Stem Density	0.055 stems/m^2
Extinction	0.3 dB/m
Ground to Volume Ratios	μ_{hh} = -12 dB μ_{hv} = -31 dB μ_{vv} = -18 dB μ_{max} = -7 dB μ_{min} = -31 dB
Scattering Coefficients	σ_{hh}= -4 dB m^2/m^2 σ_{hv}= -11 dB m^2/m^2 σ_{vv}= -8 dB m^2/m^2

Adaptation to Satellite Case

Reference Scenario for Performance Evaluation

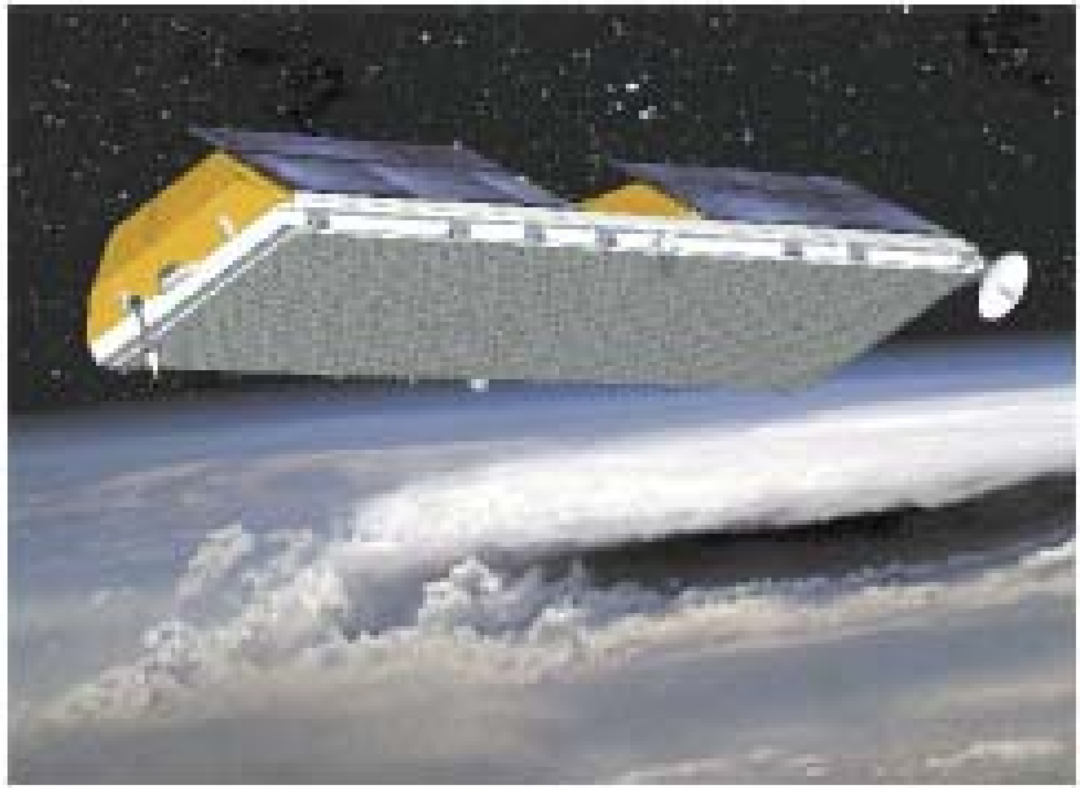
Parameter	Value
Incident Angle	35°
Volume Height	20 m
Sigma Nought	> -11 dBm^2/m^2
Minimum Ground to Volume Ratio	-26 dB
Maximum Ground to Volume Ratio	-2 dB
Extinction	0.3 dB/m

Assumptions:

- *Contributions from ground will become stronger for lower incident angles*
- *Equal scattering coefficients of -11 dB m^2/m^2 for all polarisations (worst case assumption)*

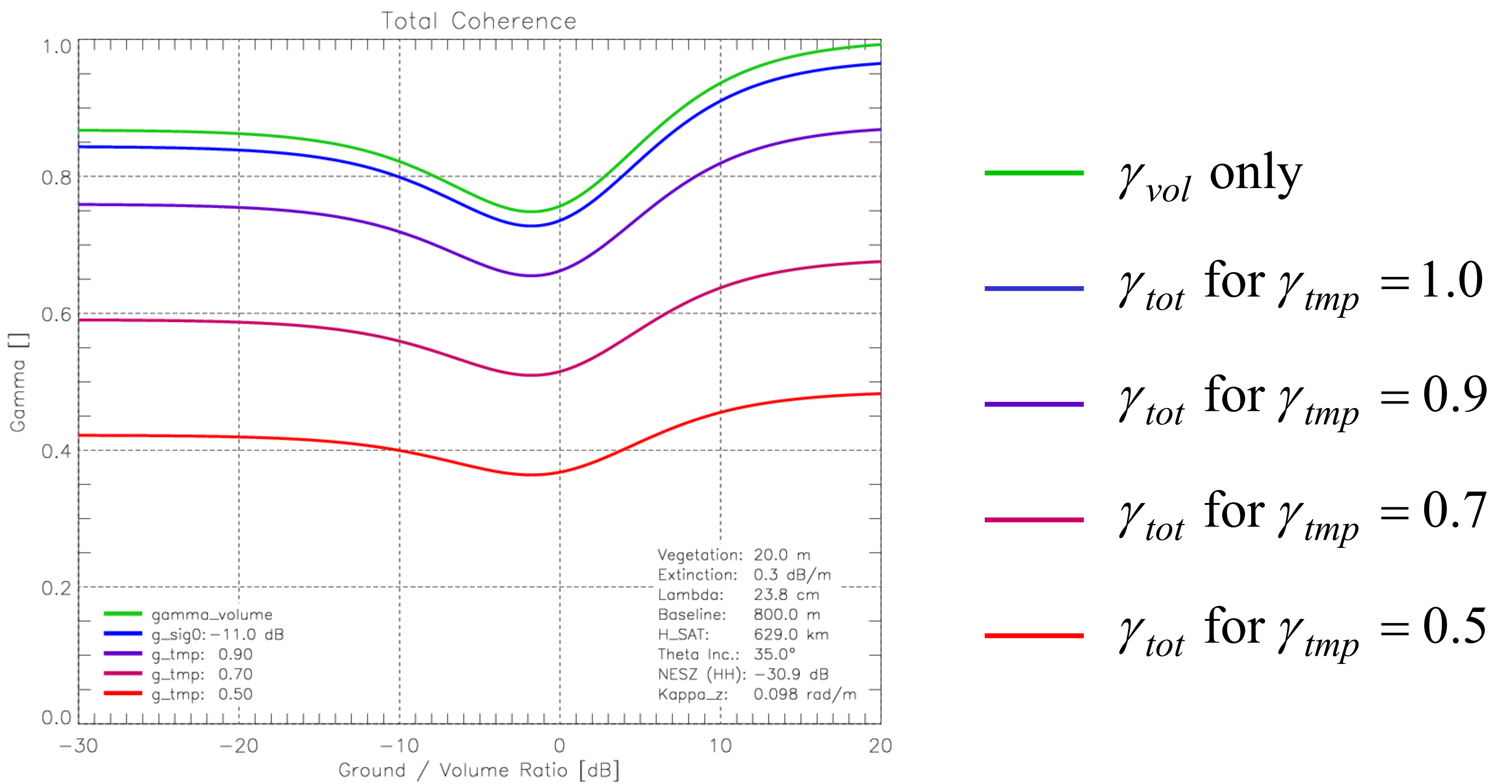
TerraSAR-L

Parameter	Value
Wavelength	0.238 m
Orbit Height	629 km
Chirp Bandwidth	80 MHz
Peak Transmit Power	6400 W (160x40W)
Duty Cycle	3,5 % (7 % / 2)
Tx Losses	1.3 dB
Noise Figure	2.5 dB
Proc. Losses	1 dB
Losses Across Swath	< 3 dB
Atmospheric Losses	1 dB
Antenna Size (Tx , Rx)	11 m x 2.86 m
Co-Registration Accuracy	1/10 pixel
Quantisation	4 bit (BAQ)
Access Range (quad pol mode)	20° - 36°



Coherence Estimation

Total Coherence: $\gamma_{tot} = \gamma_{SNR} \cdot \gamma_{vol} \cdot \gamma_{tmp} \cdot \gamma_{proc} \cdot \gamma_{quant} \cdot \gamma_{amb} \cdot \gamma_{geo} \cdot \gamma_{az}$



Computation of Height Errors

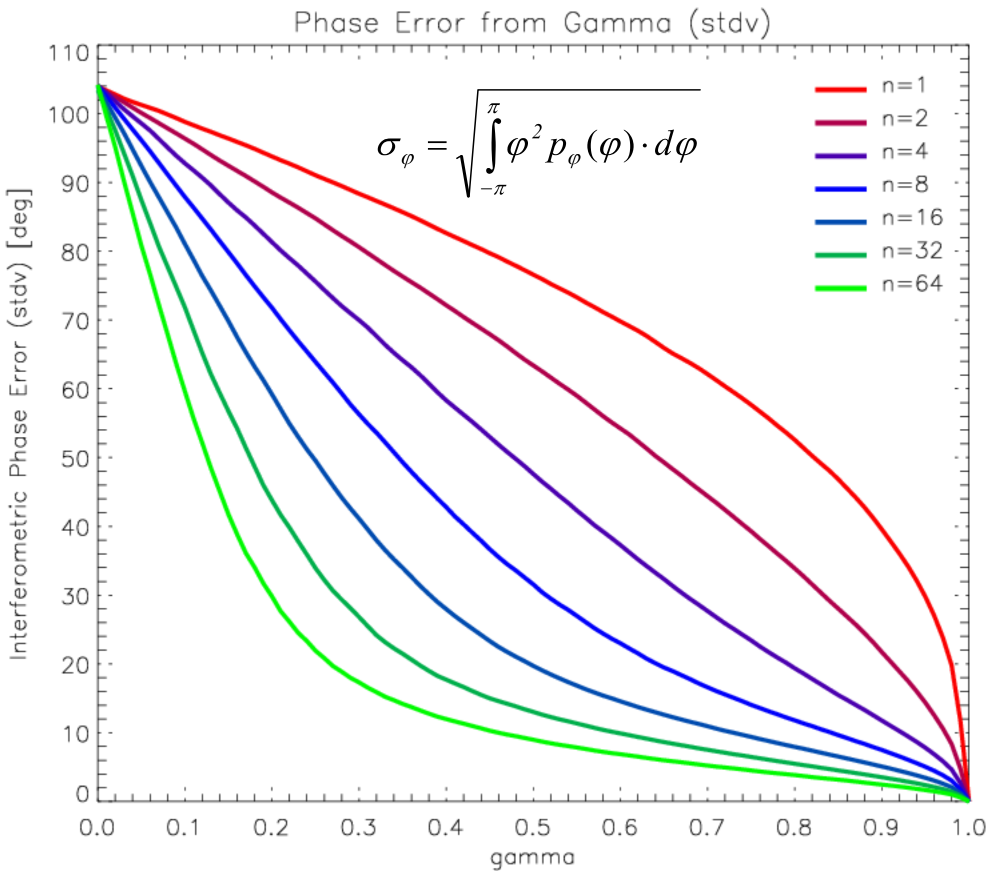
Coherence

Number of Looks

post - spacing

system & orbit parameters

Derivation of Phase Errors



$$p_\varphi(\varphi) = \frac{\Gamma\left(n+\frac{1}{2}\right)\left(1-\gamma^2\right)^n \gamma\cos\varphi}{2\sqrt{\pi}\,\Gamma(n)\left(1-\gamma^2\cos^2\varphi\right)^{n+\frac{1}{2}}} + \frac{\left(1-n^2\right)^n}{2\pi} F\left(n,1;\frac{1}{2};\gamma^2\cos^2\varphi\right)$$

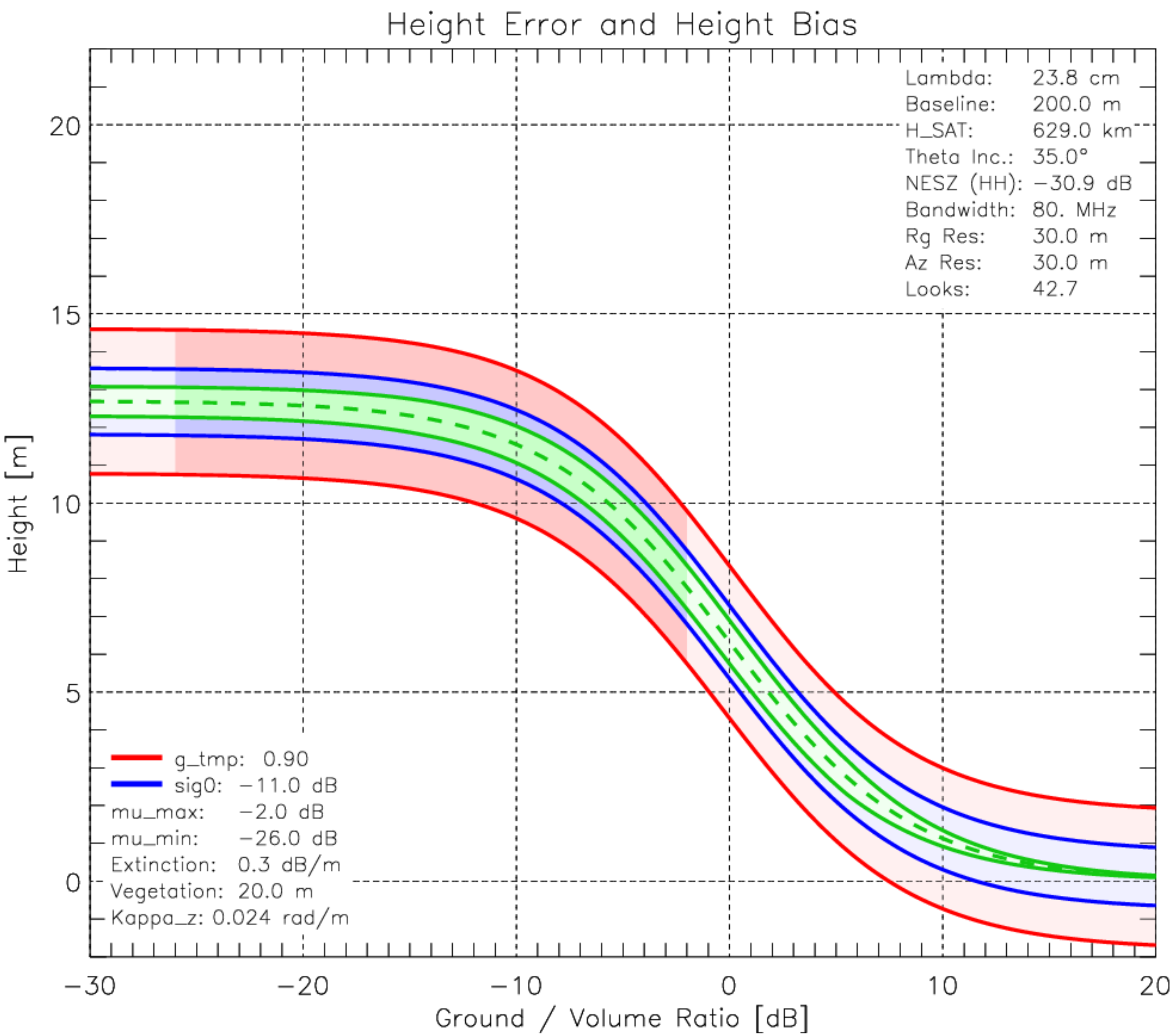
Phase to Height Conversion

$$\Delta h = \frac{\lambda r \sin(\theta_i)}{4\pi B_\perp} \cdot \Delta\varphi$$

interferometric baseline

coherence ...

Phase Tube



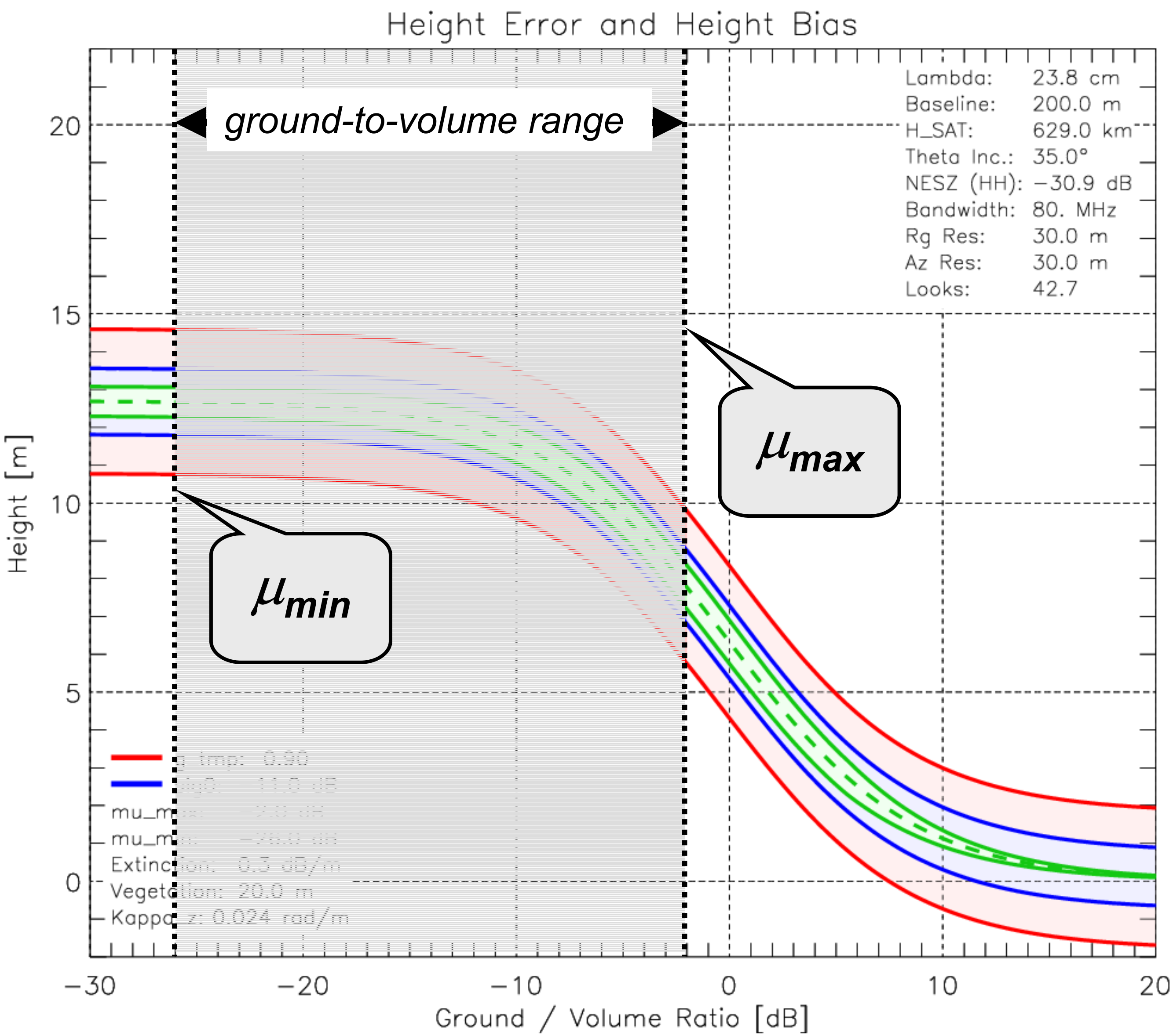
variation of phase center with different polarisations

height errors due to volume decorrelation

height errors without temporal decorrelation

height errors with temporal decorrelation (here: γ_{tmp}=0.9)

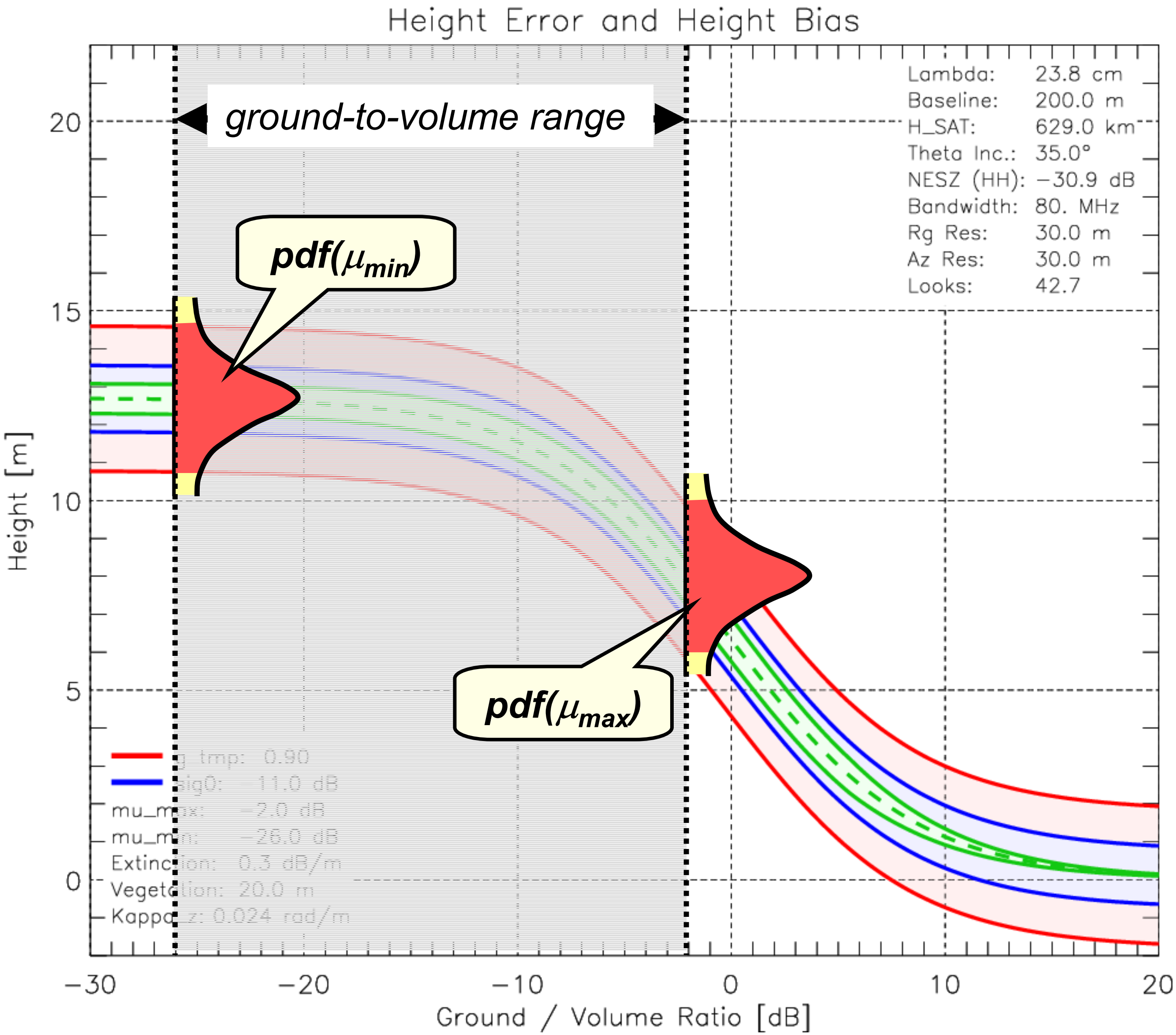
Phase Tube



Accessible Range of Ground-to-Volume Scattering Ratios by Different Polarisations:

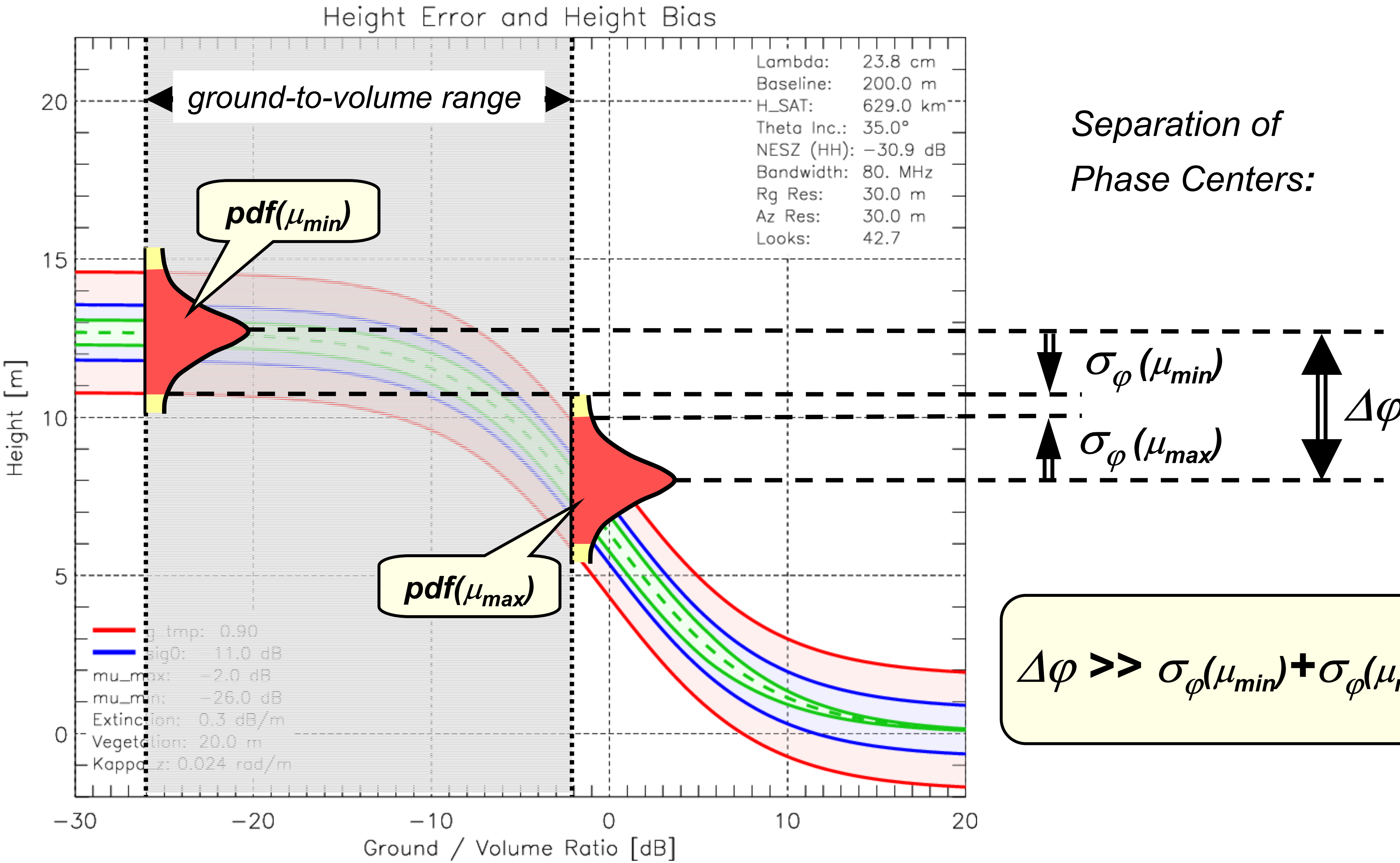
[μ_{min} , μ_{max}]

Phase Tube



pdf(μ_{min}) *and* ***pdf(μ_{max})*** *describe the probability distribution of the phase center estimates at the two extremes of the ground-to-volume range μ_{min} and μ_{max}.*

Phase Tube

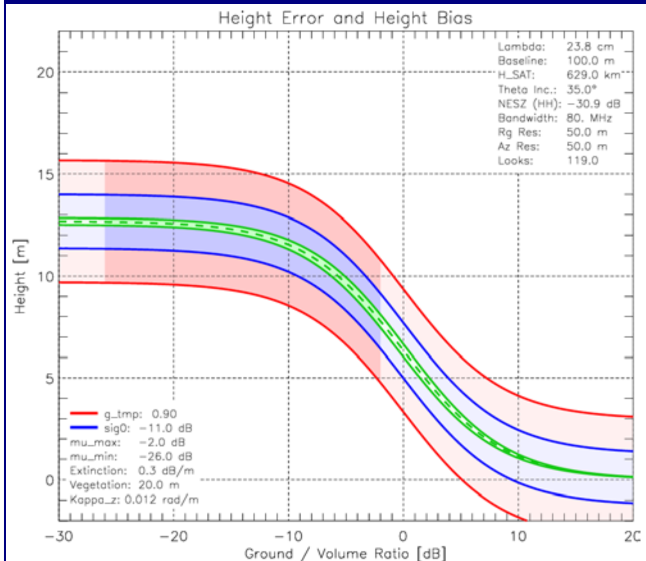


Separation of Phase Centers:

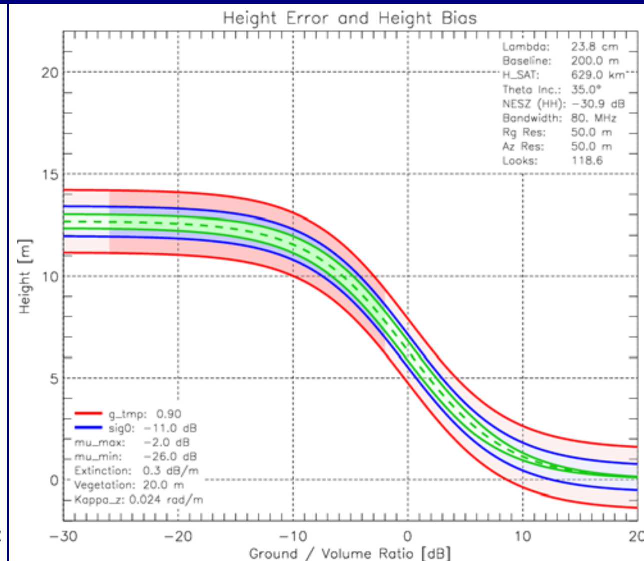
$$\Delta\varphi \gg \sigma_\varphi(\mu_{min})+\sigma_\varphi(\mu_{max})$$

TerraSAR-L (γ_{tmp} = 0.9, 50 m x 50 m)

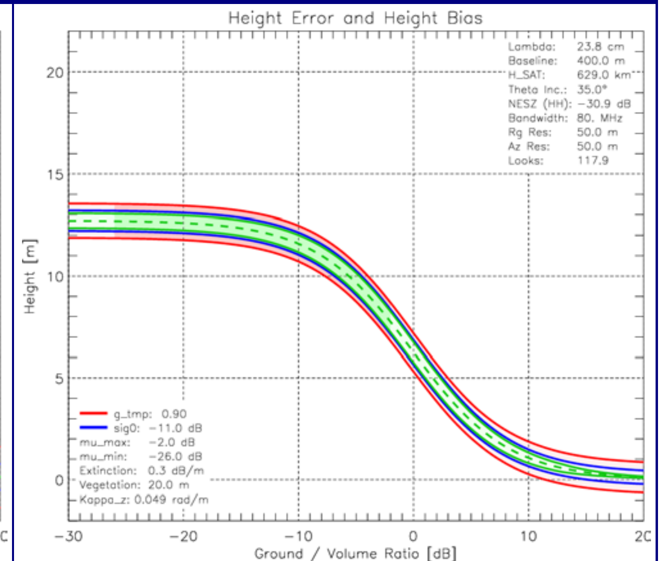
B = 100 m



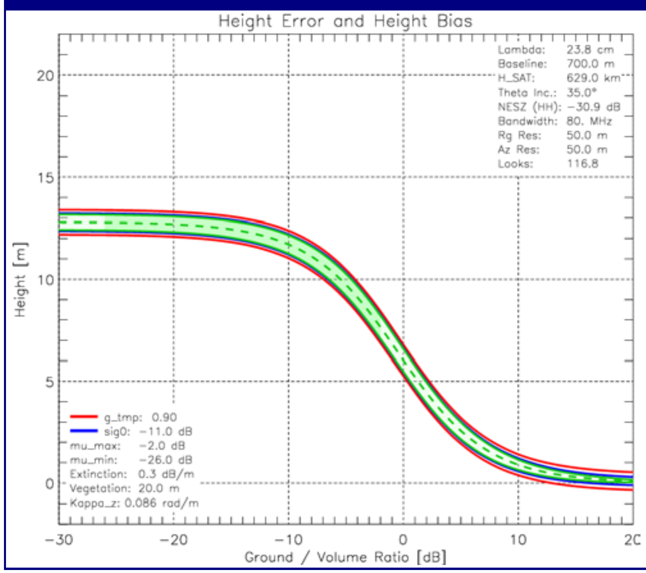
B = 200 m



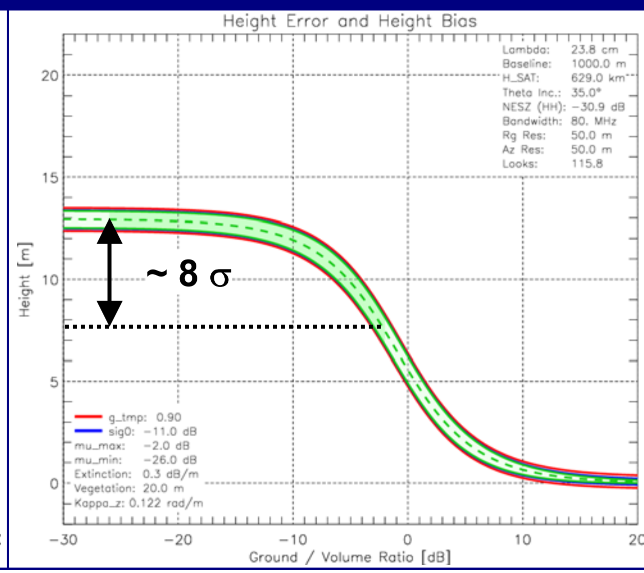
B = 400 m



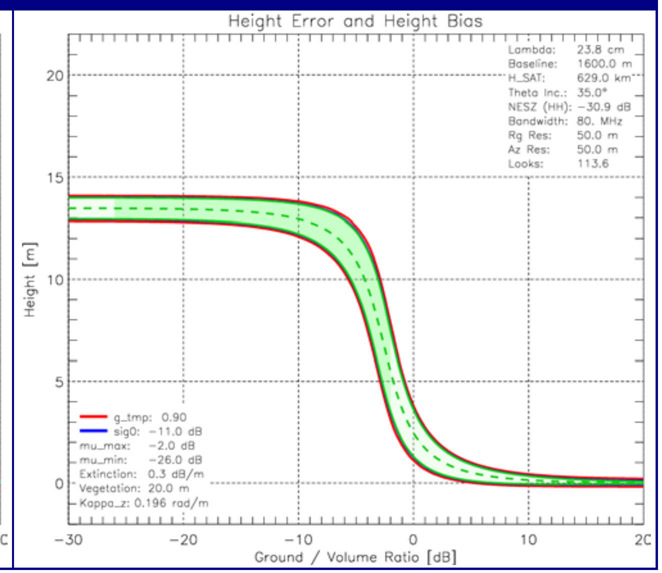
B = 700 m



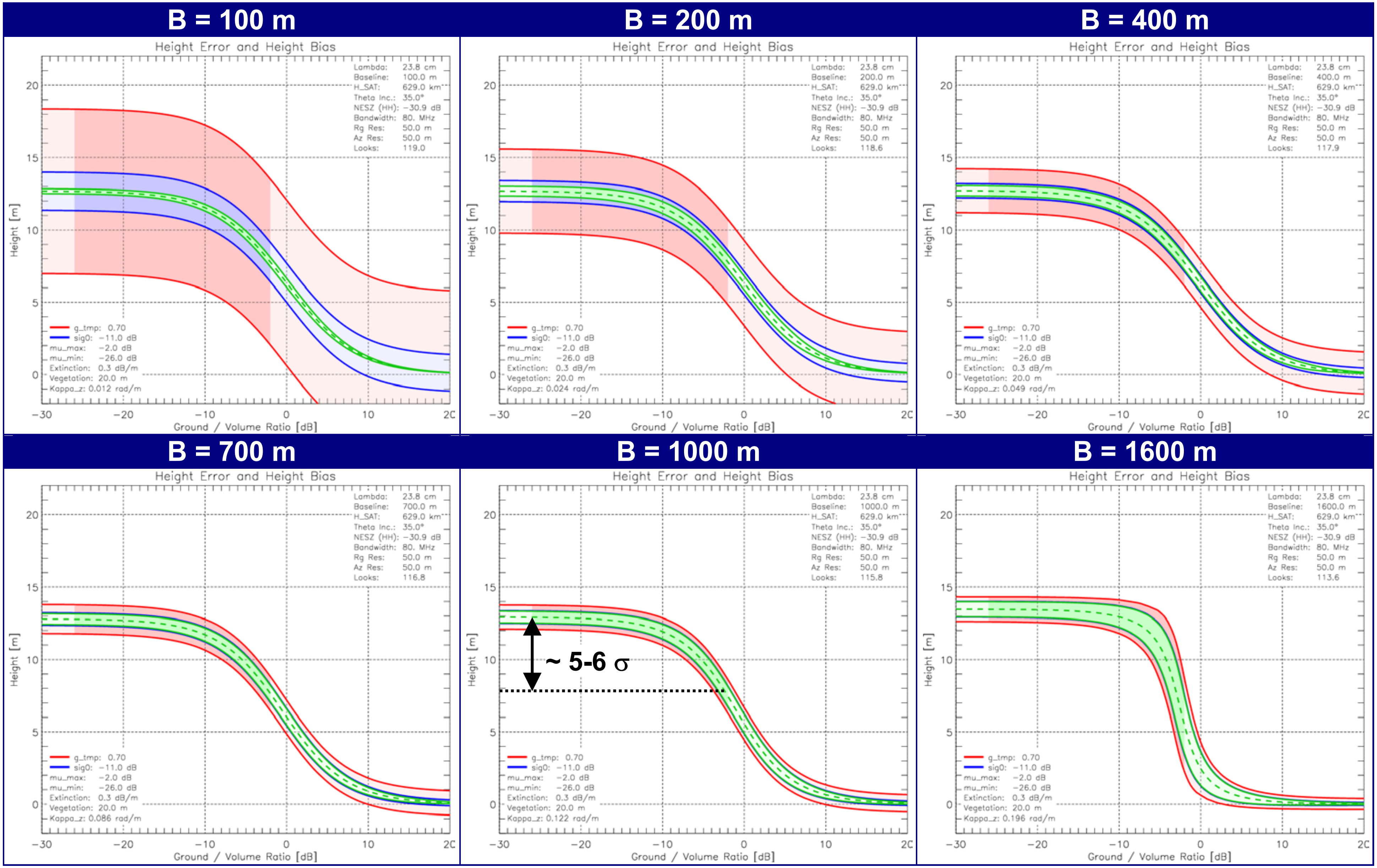
B = 1000 m



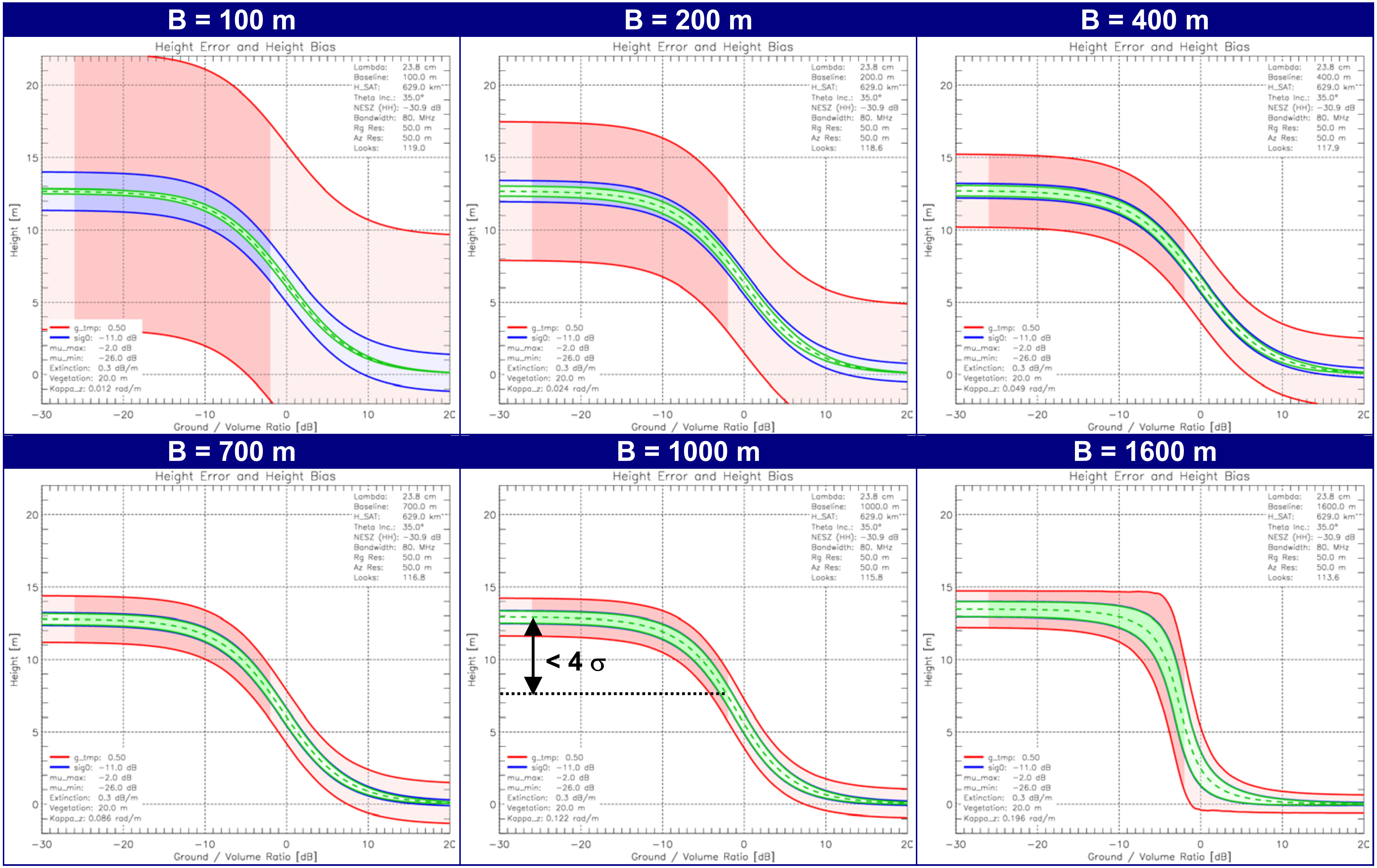
B = 1600 m



TerraSAR-L (γ_{tmp} = 0.7, 50 m x 50 m)



TerraSAR-L (γ_{tmp} = 0.5, 50 m x 50 m)

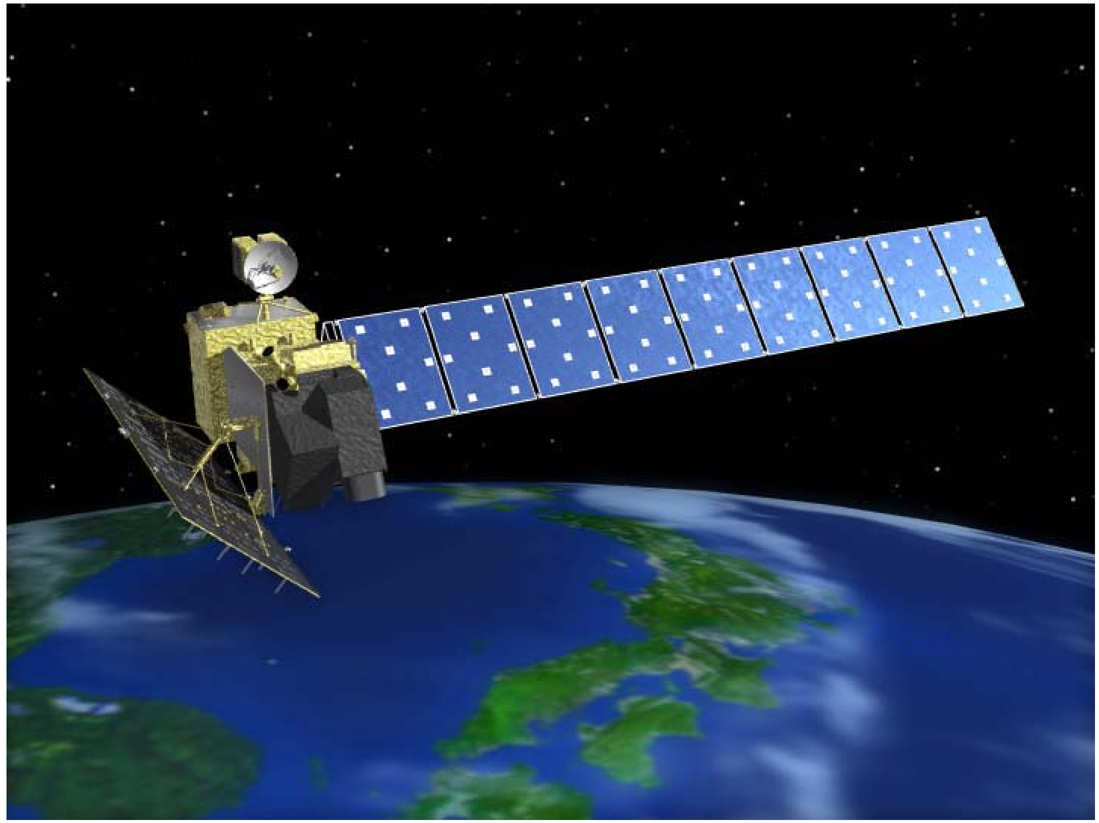


Conclusions for TerraSAR-L

- A reliable separation of the phase centres will become possible for the Scots pine forest reference scenario at low to moderate temporal decorrelation (γ_{temp} > 0.7).
- Higher temporal decorrelation (0.7 < γ_{temp} < 0.5) may require an increase of the independent post spacing.
- Optimum performance is predicted for perpendicular baselines in the order of 700 m to 1000 m assuming a forest height of 20 m (κ_z ~ 0.1 rad/m).
- The performance will strongly depend on the accessible range of ground-to-volume ratios provided by the different polarisations. This range is expected to improve for lower incident angles.

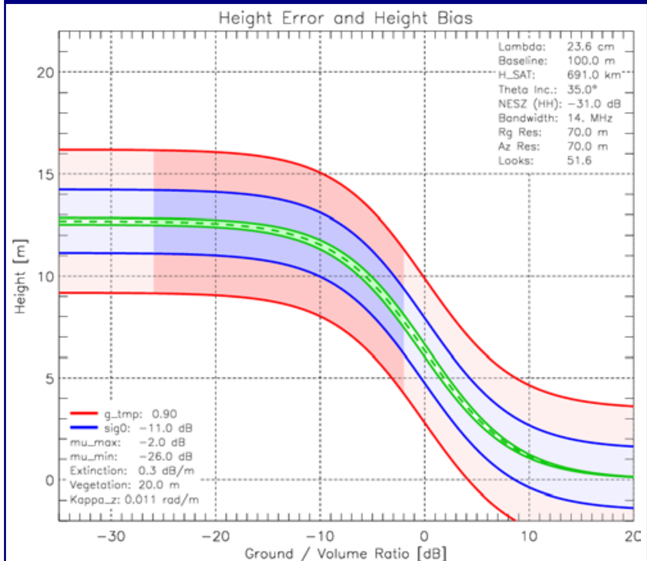
ALOS/PALSAR

Parameter	Value
Wavelength	0.236 m
Orbit Height	691 km
Chirp Bandwidth	14 MHz (quad pol.)
Peak Transmit Power	2 kW
Duty Cycle	3,5 % (7 % / 2)
Noise Figure	4 dB
Rx. + Proc Losses	1 dB
Losses across swath	< 3 dB
Atmospheric Losses	1 dB
Antenna Size (Tx , Rx)	8.9 m x 3.1 m
Co-Registration Accuracy	1/10 pixel
Quantisation	4 bit (BAQ)

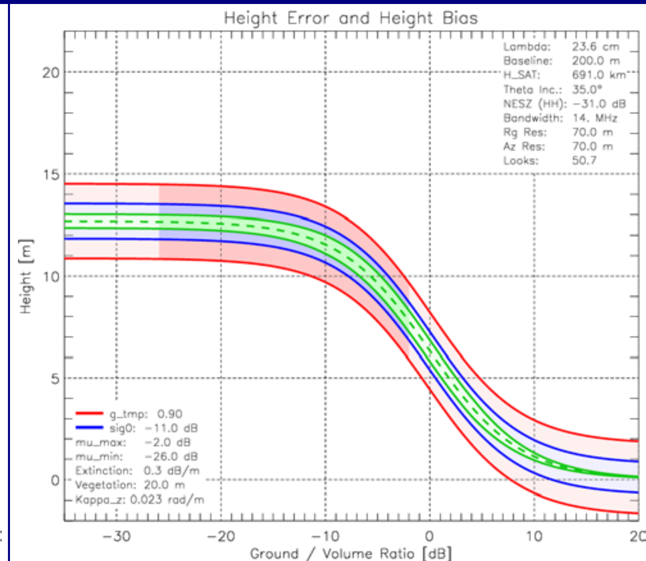


ALOS/PALSAR (γ_{tmp} = 0.9, 70 m x 70 m)

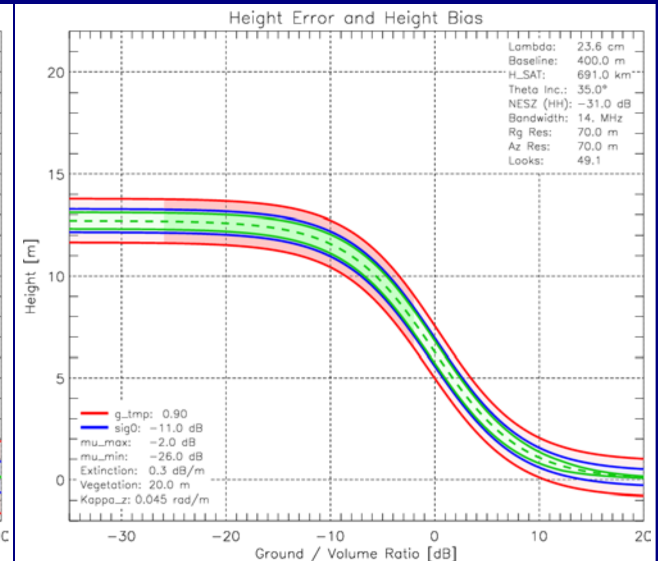
B = 100 m



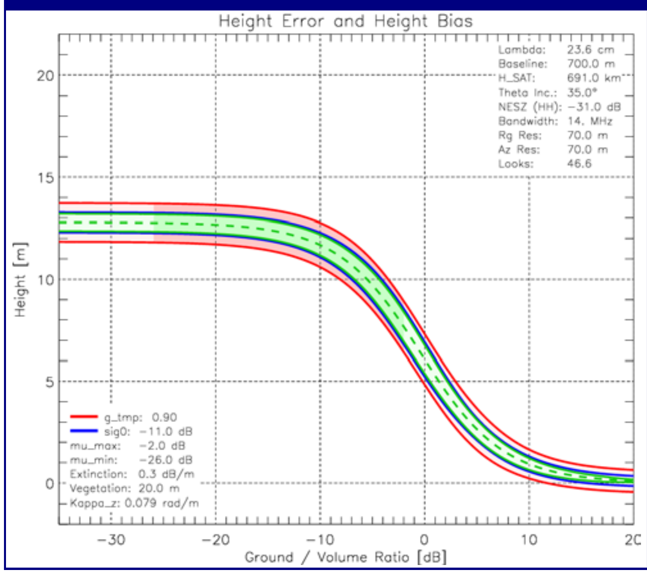
B = 200 m



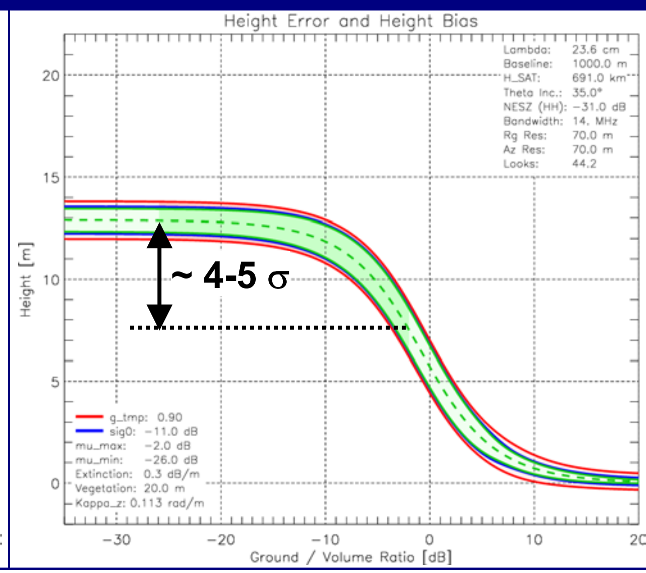
B = 400 m



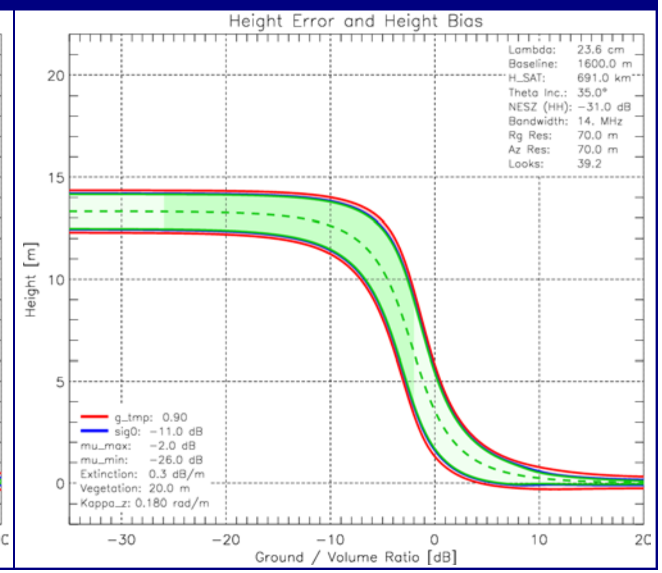
B = 700 m



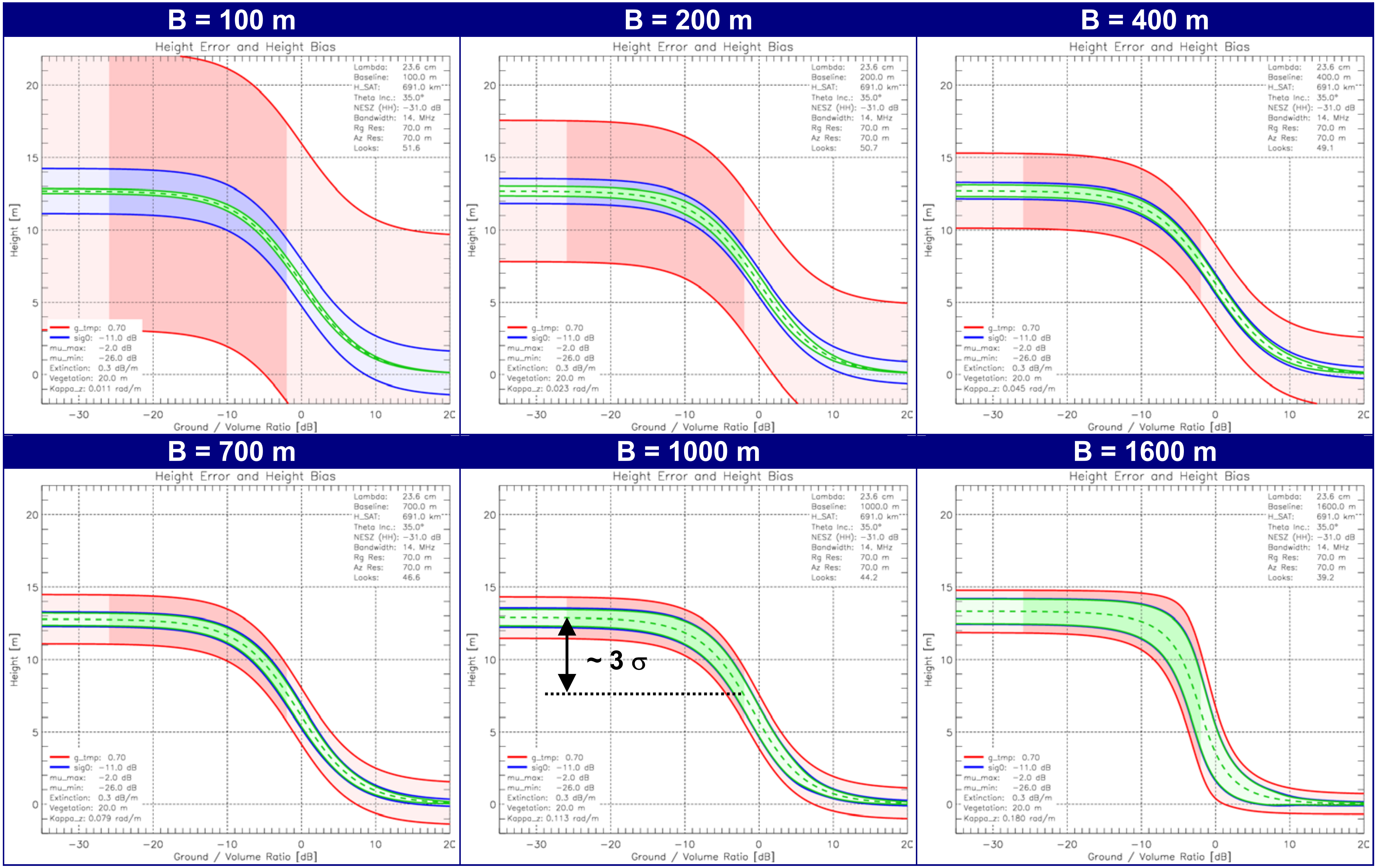
B = 1000 m



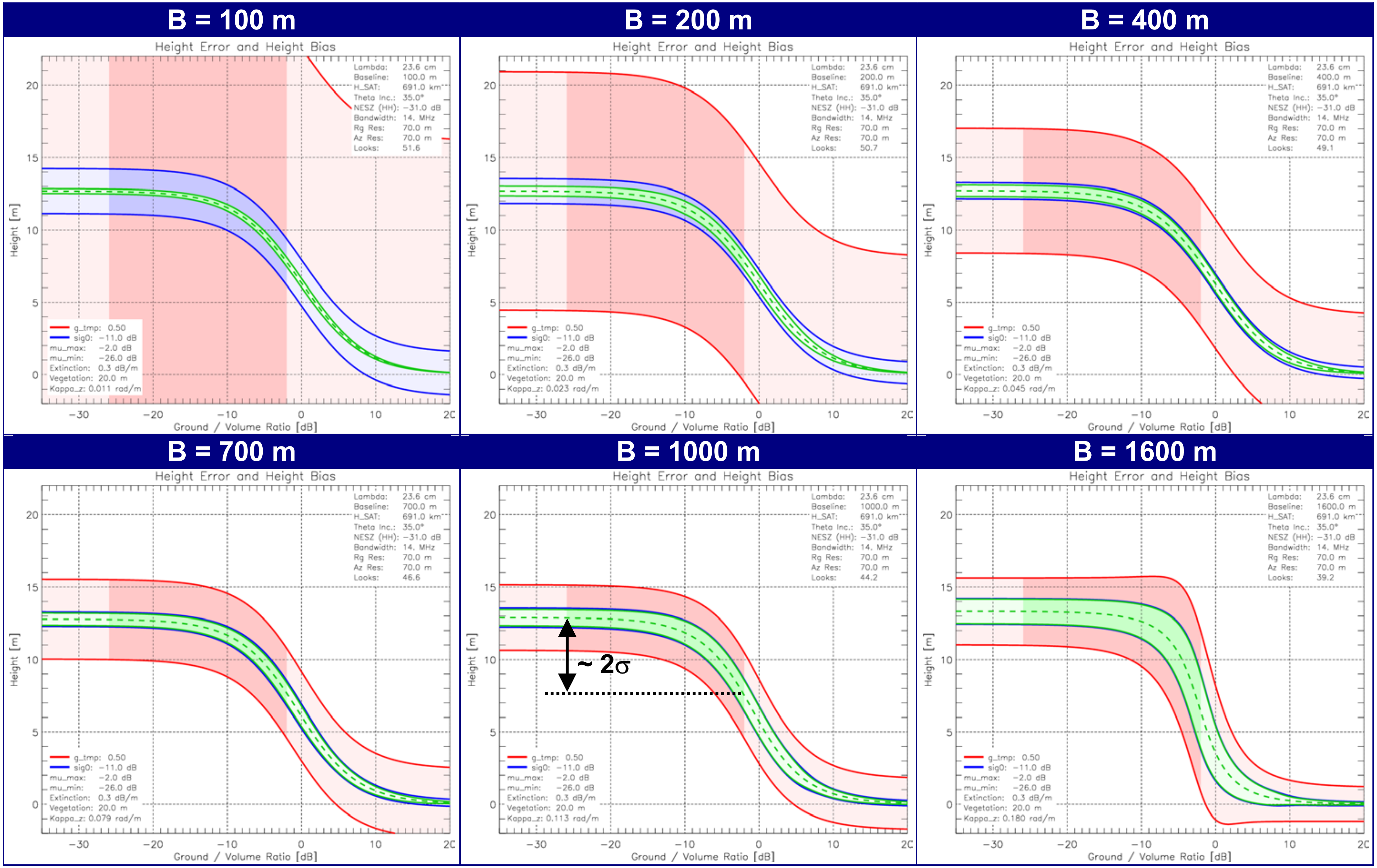
B = 1600 m



ALOS/PALSAR (γ_{tmp} = 0.7, 70 m x 70 m)



ALOS/PALSAR (γ_{tmp} = 0.5, 70 m x 70 m)

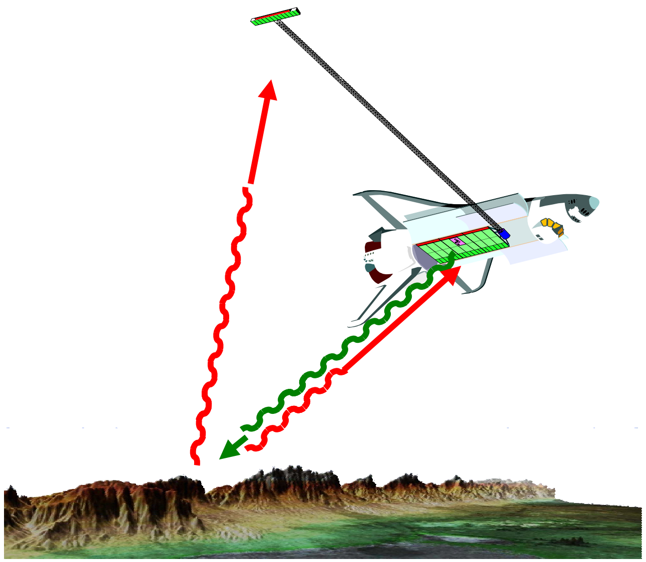
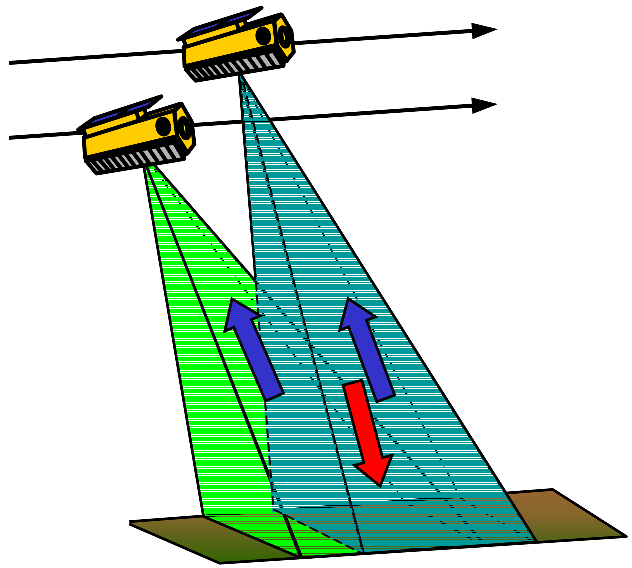
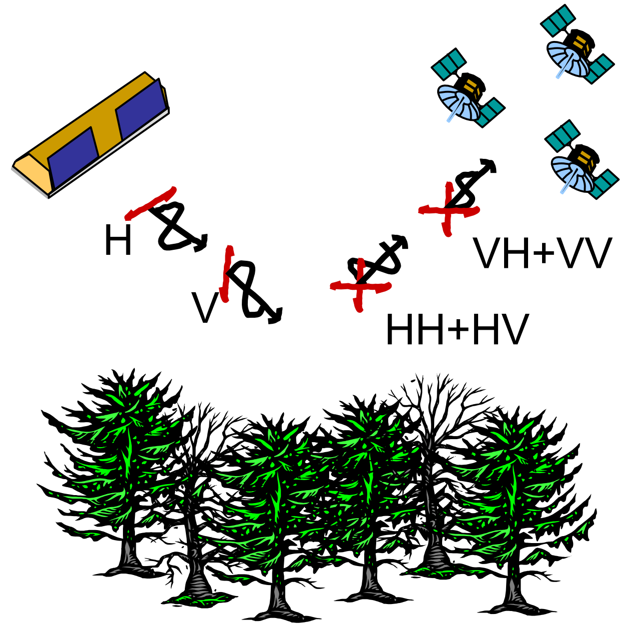


ALOS/PALSAR: Conclusions

- The performance model predicts a rather poor PolInSAR inversion accuracy for the Scots pine reference scenario assuming an independent post spacing of 70 m x 70 m.
- The poor performance prediction is mainly due to the low number of independent looks resulting from the small system bandwidth of PALSAR (only 14 MHz for fully polarimetric operation).
- An acceptable performance could be achieved by increasing the independent post-spacing.
- ALOS has a rather long repeat cycle of 46 days. Hence, lower temporal coherence has to be expected as e.g. for TerraSAR-L with a repeat cycle of 14 days.

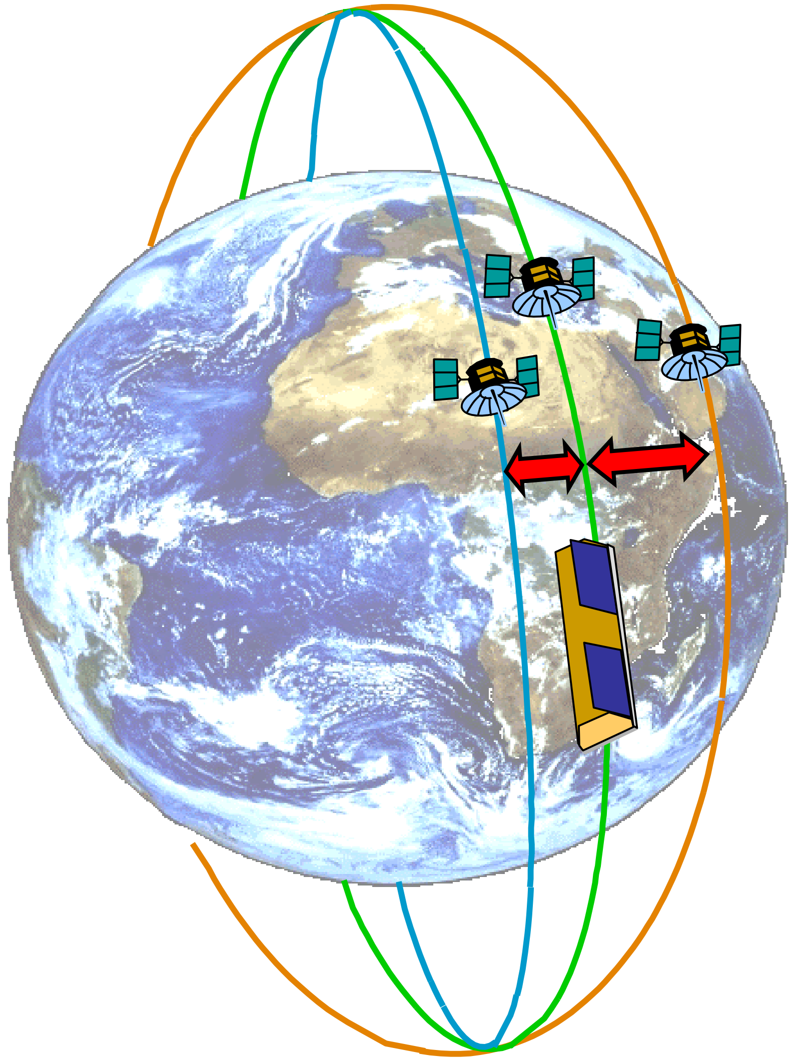
Single Pass Mission Scenarios

Single Pass PolInSAR Mission Scenarios

Satellite Boom Concepts (Precursor: SRTM)	Twin-Satellite Formations (TanDEM-X, Radarsat 2/3)	Multistatic SAR (Cartwheel, Pendulum, Voice)
		
•Maximum mast length (< 100 m) and minimum altitude (> 400 km) limit interferometric baseline •Ping-pong mode could increase interferometric baseline on the cost of higher ambiguities	•Reconfigurable system for a wide range of interferometric baselines •High sensitivity •Flexible instrument operation •Phase synchronisation in ping/pong mode	•Low cost passive receivers •Provides multiple interferometric baselines in a single pass •Increased susceptibility to ambiguities •Calibration more challenging

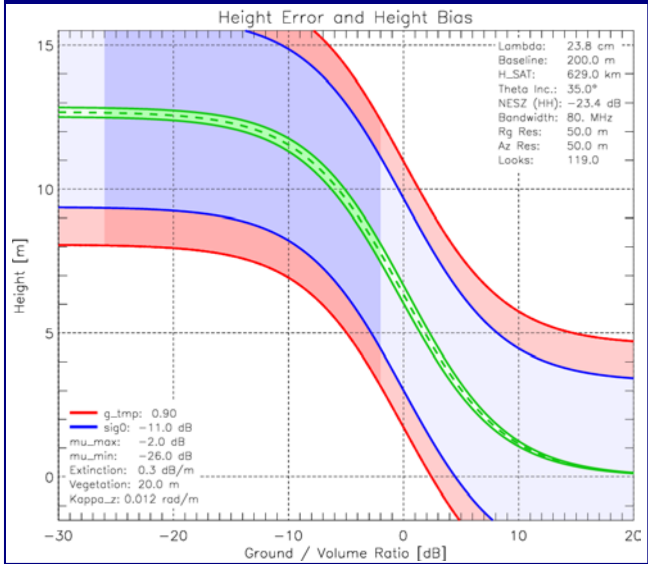
Semi-Active Interferometer with TerraSAR-L

Parameter	Value
Wavelength	0.238 m
Orbit Height	629 km
Chirp Bandwidth	80 MHz
Peak Power (radiated)	4.4 kW
Duty Cycle (altern. pol.)	3,5 % (7 % / 2)
Noise Figure	2.5 dB (incl. swath)
Losses (proc., swath, …)	< 6 dB
Antenna Size (Tx)	11 m x 2.86 m
Antenna Size (Rx)	circular: 3 m
Proc. Bandwidth	1200 Hz
Co-Registration Acc.	1/10 pixel
Quantisation	4 bit (BAQ)
Incident Angle	35°
Along-Track Displ. (Rx)	1 km
Antenna Size (Tx)	11 m x 2.86 m
Sigma Nought	> -11 dBm^2/m^2 (HH,VV) > -14 dBm^2/m^2 (HV,VH)
Post Spacing	50 m x 50 m
Extinction	0.3 dB/m
Volume Height	20.0 m

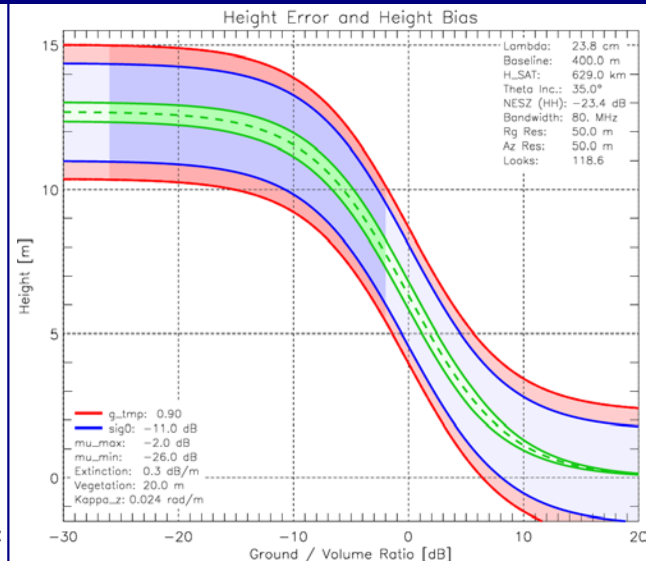


TerraSAR-L Cartwheel (γ_{tmp} = 0.9, 50 m x 50 m)

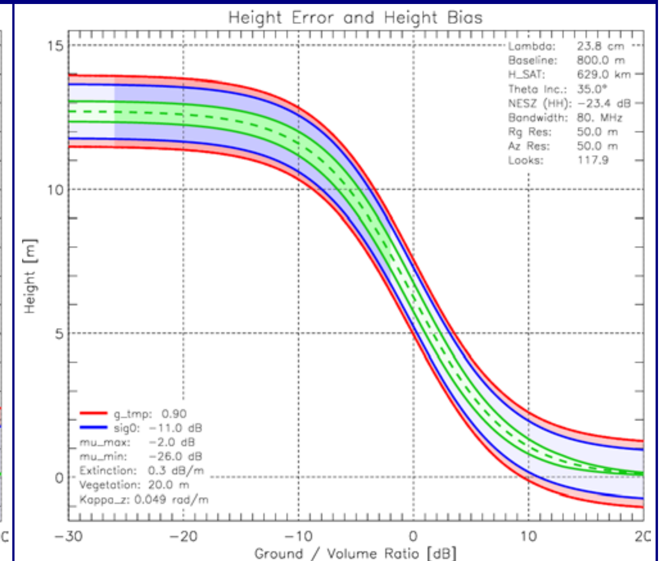
B = 200 m



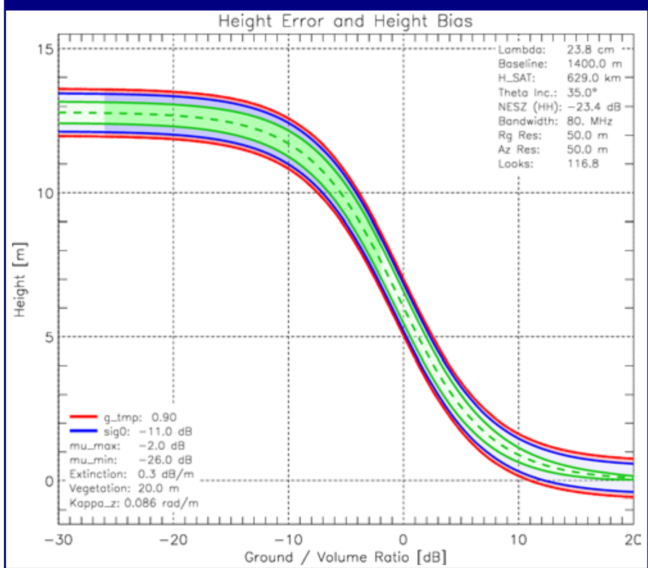
B = 400 m



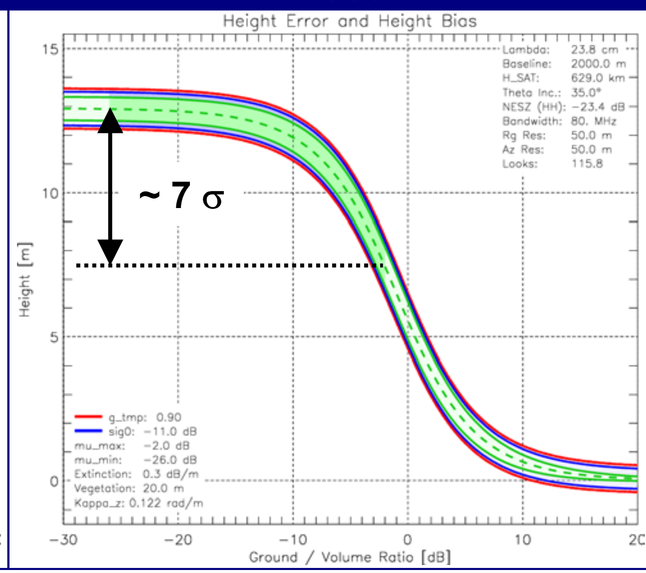
B = 800 m



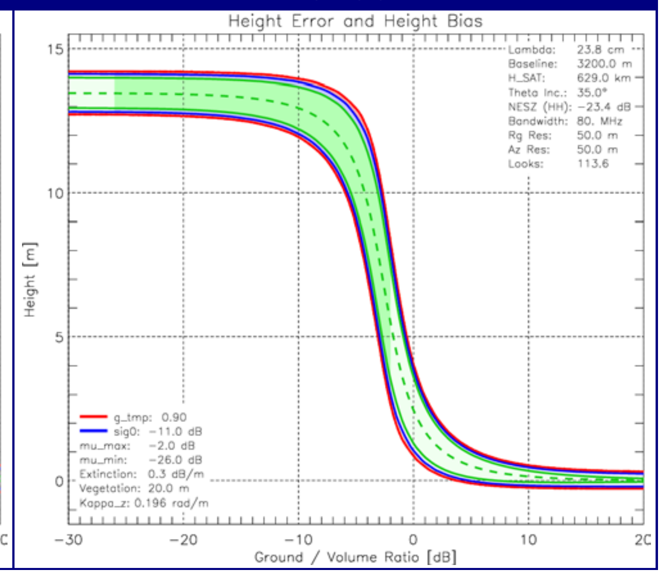
B = 1400 m



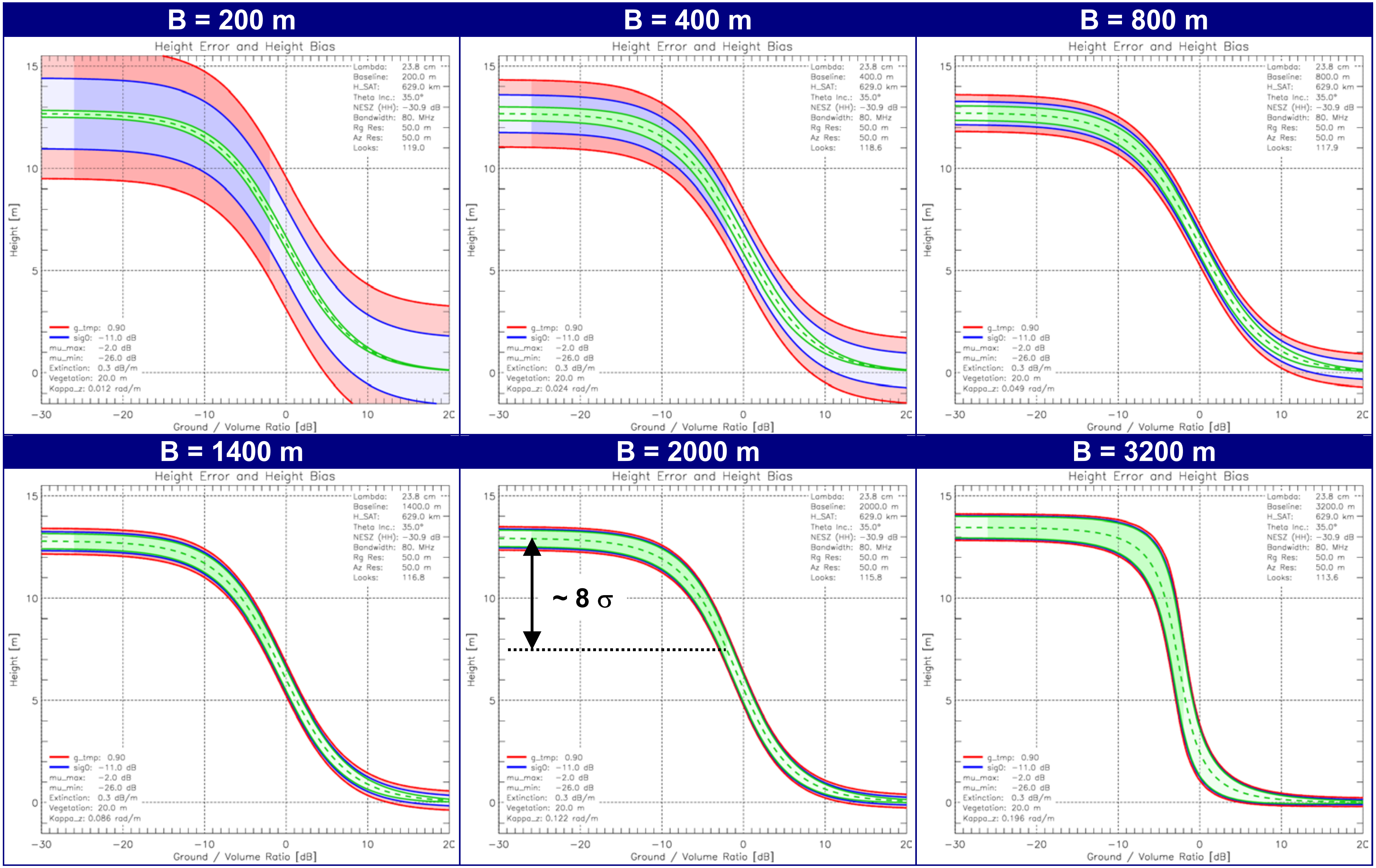
B = 2000 m



B = 3200 m



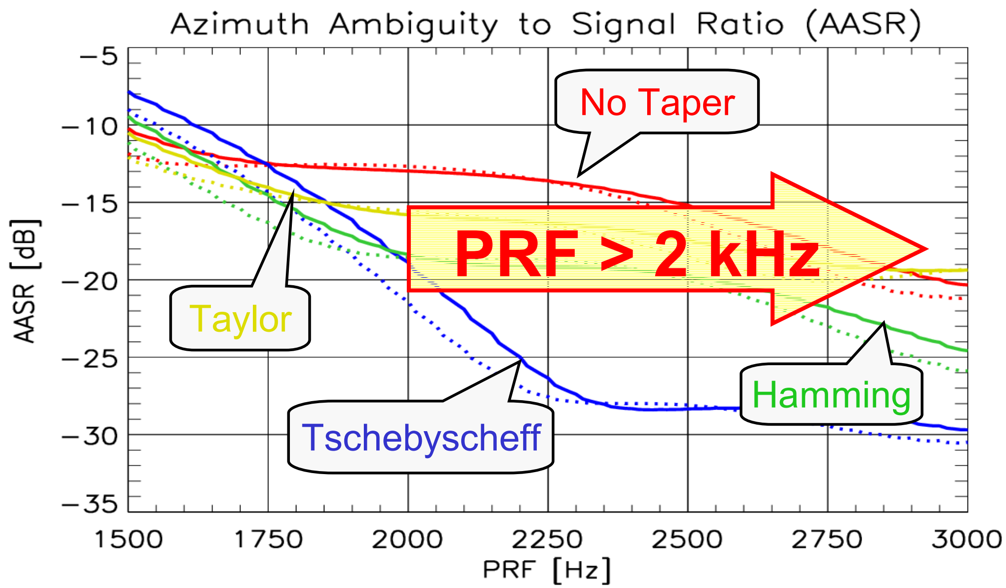
TerraSAR-L Tandem (γ_{tmp} = 0.9, 50 m x 50 m)



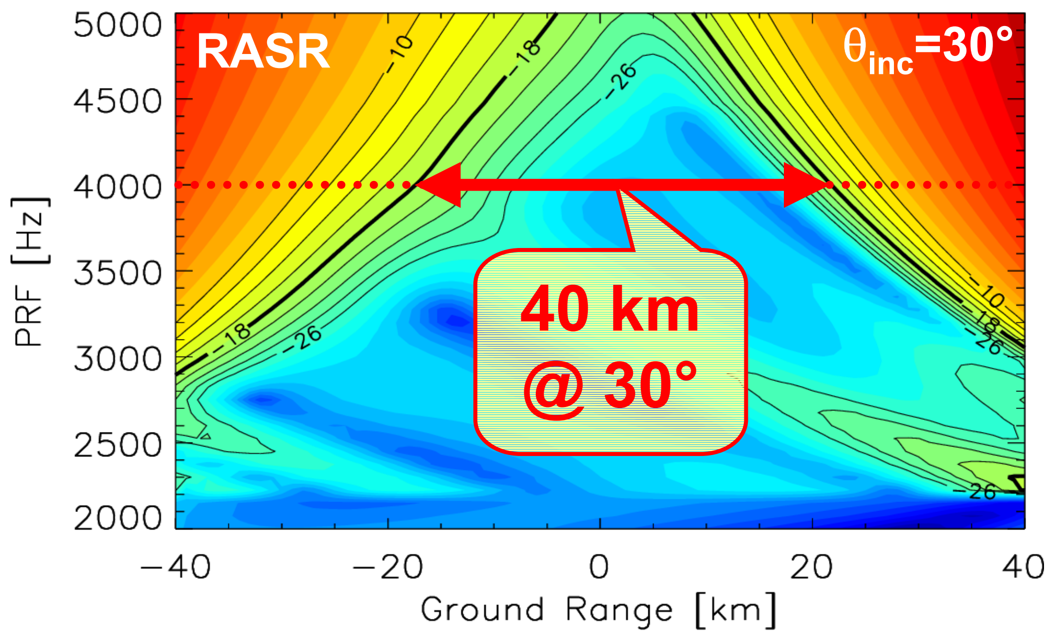
Critical Issues

Ambiguities

- ***Azimuth Ambiguities***
  - cartwheel–like configurations have an increased susceptibility to ambiguities due to the small Rx-antennas
  - azimuth ambiguities in cartwheel like configurations may be reduced by an appropriate tapering of the transmit antenna



- ***Range Ambiguities***
  - a fully polarimetric mode requires alternating transmit polarisations which will increase the PRF by a factor of two
  - range ambiguities will limit the unambiguous swath width at shallow incident angles (e.g. 40 km @ 30° and 12 km @ 35° in TSL-CW)



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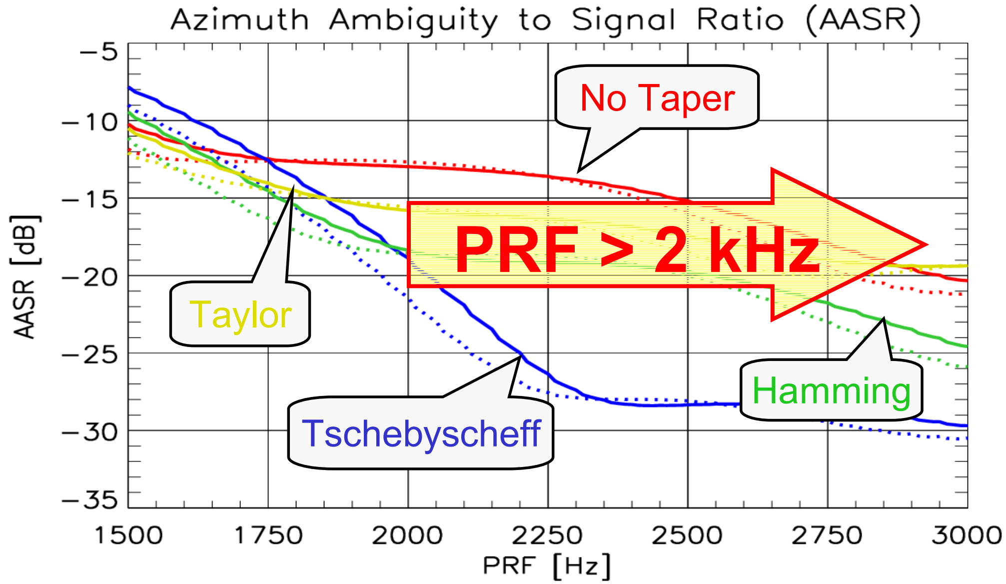

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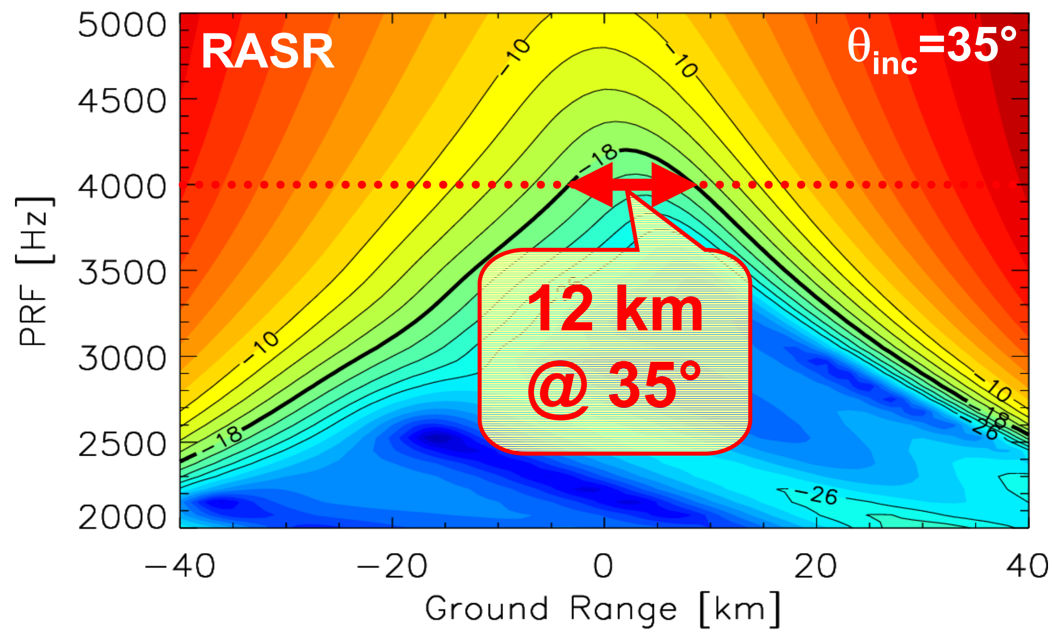
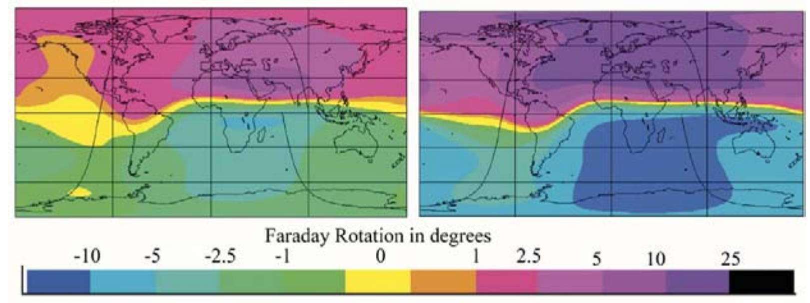


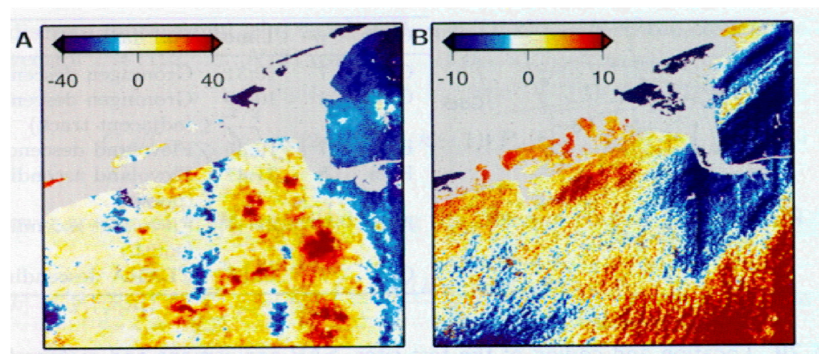
Propagation Errors

- ***Faraday Rotation***
  - may become several 10th of degrees (L-band, solar max.)
    - → *single pass:* equal rotation for all channels (less critical for most PolInSAR applications)
    - → *repeat pass:* differential rotation within interferometric channels
  - correction of Faraday rotation possible within 3° to 5° (cf. Freeman, 2004)
  - open issues: (1) tolerance level for different PolInSAR applications
    (2) bistatic angle in cartwheel configurations



Predictions of one-way Faraday rotation in L-Band for low (left) and high (right) solar activity (P. Wright, 2003)

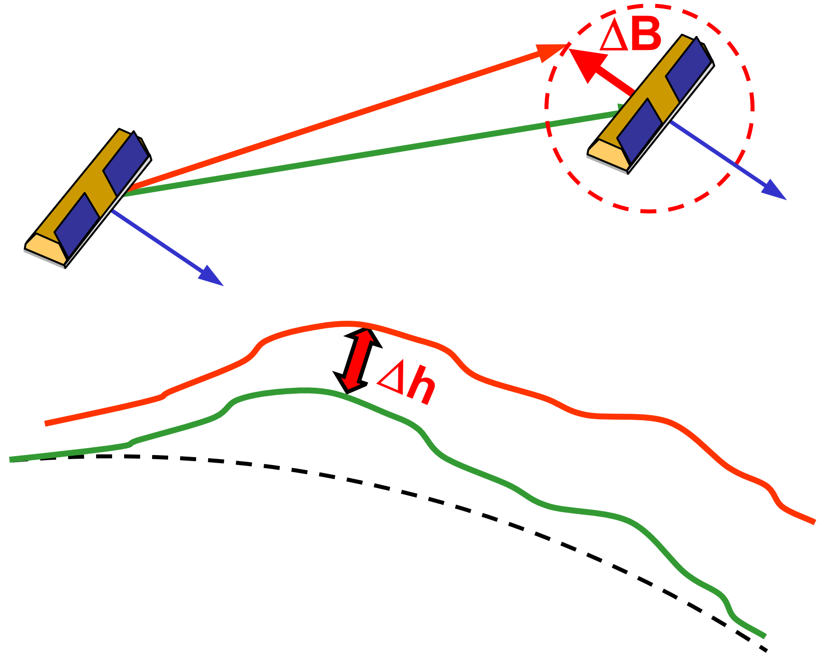
- ***Atmospheric Disturbances***
  - different atmospheric conditions may cause phase disturbances in repeat pass InSAR
  - low frequency bias of ground topography phase, residual PolInSAR parameters are less affected
  - becomes more severe for shorter wavelengths



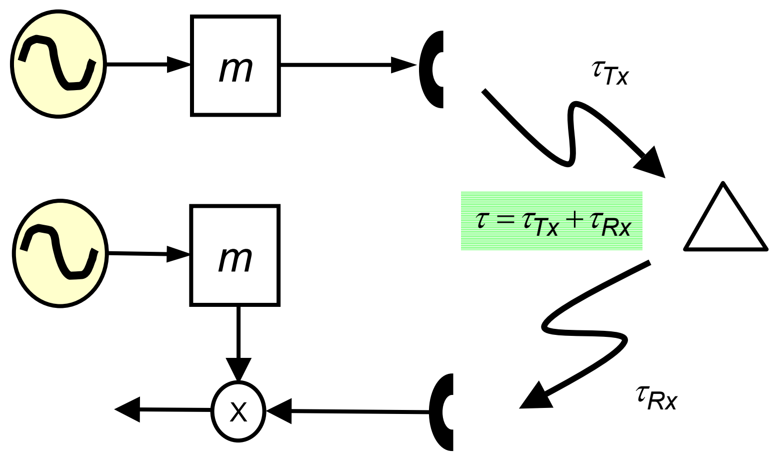
Atmospheric signal of ERS-tandem in millimeters zenith delay from (R. Hanssen, 2001)

Baseline and Oscillator Errors

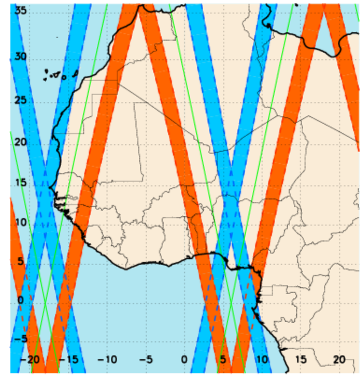
- ***Baseline Estimation Errors***
  - will mainly affect estimates of the absolute ground topography phase φ_0
  - may also introduce a slight bias in the inversion process due to the use of a wrong $\Delta\theta$
  - single-pass configurations enable precise estimation of baseline vector with mm accuracy based on relative GPS carrier phase evaluations

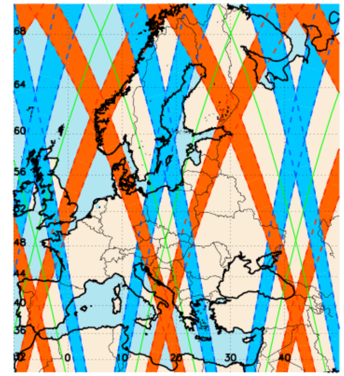


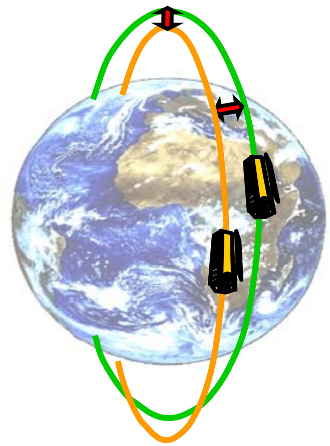
- ***Oscillator Phase Errors***
  - mainly affect single pass configurations in bistatic mode
  - uncorrelated oscillator noise will introduce low frequency phase errors in azimuth
  - will mainly affect estimates of the absolute ground topography phase φ_0

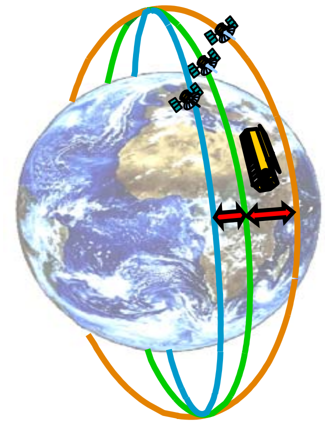


Satellite Orbits



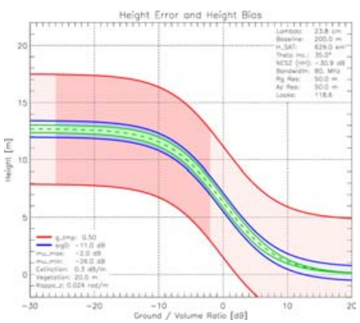


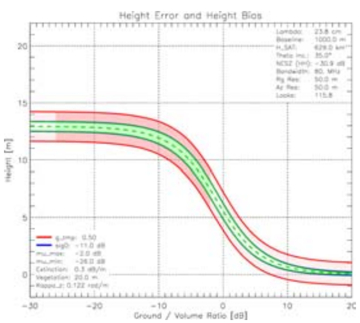


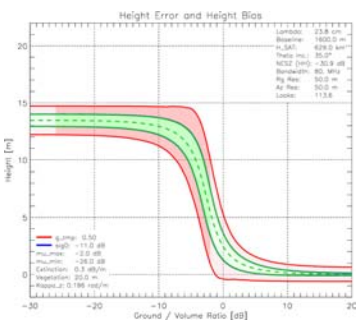


- ***Orbit Selection***
  - repeat pass missions require short repeat cycles to minimize temporal decorrelation
  - short repeat cycles cause large gaps between the ground tracks, thereby requiring a wide range of incident angles to achieve global coverage
  - single pass missions require appropriately designed satellite formations to provide the desired baselines and to avoid any collision risk

- ***Baseline (κ_z) Optimisation***
  - the PolInSAR performance depends strongly on the chosen interferometric baseline
  - system optimization requires some a priori knowledge about the imaged scene or an acquisition with multiple baselines





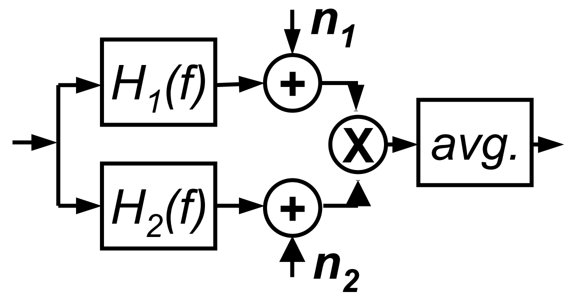


Processing & Calibration

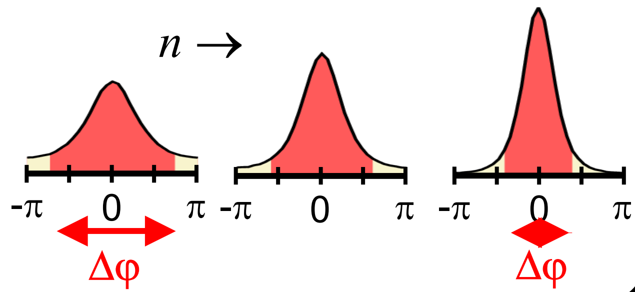
- ***Temporal Decorrelation and Multi-Looking***
  - the current performance analysis uses the multiplicative coherence model, i.e. temporal errors are modelled as additive white Gaussian noise in each SAR image
  - is such a model appropriate ? (precipitation and wind may also cause a local shift of the phase centres)
  - should we hence expect correlated errors between adjacent resolution cells ? Will multi-looking reduce temporal phase errors in the predicted manner ?
  - Are all polarisations affected in the same way ? (ground and volume may be affected differently)
- ***Bistatic Calibration***
  - bistatic acquisitions may require new calibration techniques (e.g. due to invisible corner reflectors for large bistatic angles)

$$\gamma_{tot} = \gamma_{temp} \cdot \gamma_{SNR} \cdot \gamma_{vol} \cdots$$

$$\gamma_{SNR} = \frac{1}{\sqrt{1+SNR_1^{-1}} \cdot \sqrt{1+SNR_2^{-1}}}$$



$$pdf_{\varphi}(\varphi) = f(\gamma, n)$$



Conclusions

- Repeat pass missions will suffer from significant deteriorations due to temporal decorrelation.
- The application area of boom interferometers is very limited due to the short baseline length.
- Satellite formations avoid temporal decorrelation and offer the opportunity to acquire interferometric data with arbitrary baseline lengths in a highly flexible and reconfigurable geometry.
- No show stopper has been found for the implementation of a multi-satellite single pass PolInSAR mission, but a careful mission design will be required.